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Title: **High Performance Computing for Domestic Petroleum Reservoir Simulation**

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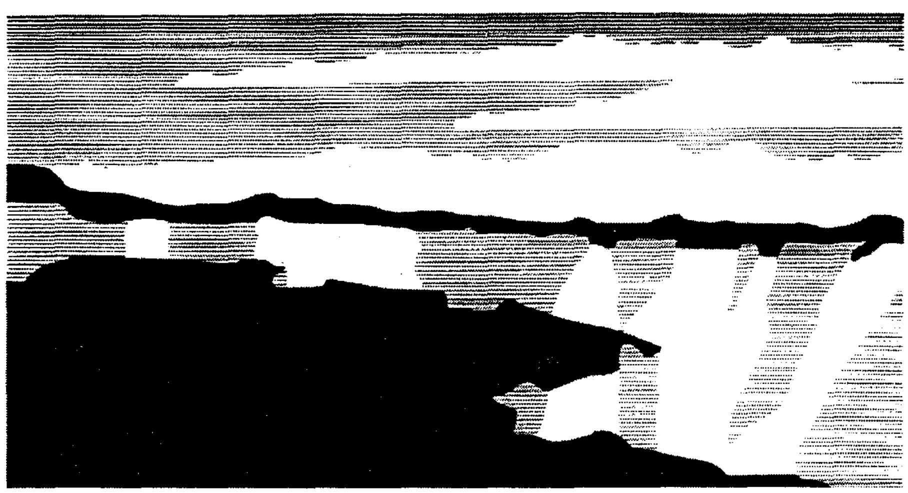

Los Alamos
NATIONAL LABORATORY

High-Performance Computing for Domestic Petroleum Reservoir Simulation

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Abstract

This is the final report of a two-year, Laboratory-Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). High-performance computing offers the prospect of greatly increasing the resolution at which petroleum reservoirs can be represented in simulation models. The increases in resolution can be achieved through large increases in computational speed and memory, if machine architecture and numerical methods for solution of the multiphase flow equations can be used to advantage. Perhaps more importantly, the increased speed and size of today's computers make it possible to add physical processes to simulation codes that heretofore were too expensive in terms of computer time and memory to be practical. These factors combine to allow the development of new, more accurate methods for optimizing petroleum reservoir production.

1. Background and Research Objectives

Domestic oil production is declining as much as 5 to 10 percent per year. In the U.S. oil industry, there has been a decline of more than 460,000 jobs, with more likely to come. Changes in policy, regulation and price structure could exert a rapid positive effect on the gas industry, but basically the decline is due to the fact that primary production is past for U.S. fields in the lower forty eight states. The industry has recognized that a substantial portion of the unproducible or uneconomic reserves of oil and gas in the U. S. can be recovered with near-term technology and with improved reservoir management (i.e., engineering design, optimization, and monitoring). For example, it has been estimated that an additional 70 billion barrels of oil can be recovered by identified technologies with the application of well-designed research and development and technology transfer strategies. To put this number in perspective, approximately 140 billion barrels of oil have been produced in the U.S. since production began in 1859. This increase would sustain current levels of U.S. oil production

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for decades, which is necessary for an orderly transition to alternative transportation fuels, and could provide a means to arrest the trends in oil and gas industry employment.

We sought to develop a research project in collaboration with the oil and gas industry which would focus on research and development needs in exploration and production sciences. In particular, we sought to address the areas of reservoir simulation on massively parallel machines, multigrid methods for reservoir simulation, and fluid flow and deformation in Gulf sediments. Each of these areas represents computational research and development at the existing state-of-the-art, and each has a major oil and gas company partner. All of the proposed work and research products are nonproprietary, and results will be generally available to interested parties.

Recognizing that improved oil and gas recovery can only be brought about by better reservoir engineering and better reservoir management, leading companies in the petroleum industry have maintained large research facilities for the purpose of using supercomputing methods to predict the location of oil reservoirs and reservoir performance (i.e., determining maximum oil recovery utilizing optimal field and recovery process design). Previously, most of these companies developed these methods independently as proprietary research and development. However, as the cost of these activities have increased, even the largest of the petroleum companies have concluded that this work is simply too expensive to be handled in a proprietary process. Focused research teams combine the computational and geosciences capabilities of the DOE weapons laboratories with industry researchers. The massively parallel computing capabilities needed for the proposed projects are required for this work. It is this combination of industry and Laboratory capabilities and facilities that differentiates these teams from the past efforts in this area.

Massively parallel reservoir simulation and the enhancement of multigrid methods provide the opportunity to optimize reservoir performance in the face of heterogeneity without loss of resolution. Better explanation of fluid flow in deforming media and pore-scale geochemistry provides clues for the location of petroleum resources based upon geologic and diagenetic data.

2. Importance to LANL's Science and Technology Base and National R&D Needs

This project supports Los Alamos core competencies in theory, modeling, and high-performance computing as well as earth and environmental systems. It enhances LANL's visibility in the oil and gas area and increases our ability to respond to initiatives in those areas. This project is important to the Laboratory because it draws on the background in unstructured meshes that was developed in the weapons program and the LANL semiconductor project and uses that experience for geological modeling. The constraints placed on the numerical grids by reservoir simulation and the collaboration with the grid team have improved the product for the weapons application as well.

3. Scientific Approach and Results to Date

This project resulted from our interest in unstructured (finite element) grids as well as the interest of our industrial partners (primarily Western Atlas Software). Unstructured numerical meshes, consisting of triangles in two dimensions and tetrahedra in three dimensions, are experiencing a growth in popularity in oil reservoir simulation because of their ability to model complex phenomena such as faults and non-vertical wellbore systems. This project conducted research in three areas related to unstructured grids: the development of software for creating unstructured meshes, benchmarking the performance of unstructured meshes with structured meshes, and the development of linear equation solvers for use with unstructured grids.

The unstructured mesh generation work consisted of creating multiply defined nodes to model faults and interfaces accurately and developing a capability for combining meshes developed separately into a common mesh. The multiply defined node work consisted of major code modifications to allow coincident nodes to exist. On a fault, for example, three nodes could exist simultaneously at a point, one node representing the rock to one side of the fault, one node representing the fault and its flow properties, and another representing the rock on the other side of the fault. Fault offsets are easily modeled with this arrangement, as well as flow within the plane of the fault. The connectivity arrays and property values are easily accounted for. Flow between the coincident nodes is accomplished by forcing thermodynamic and mechanical equilibrium between the nodes. The multiply defined nodes add complication to the solution of the resulting equations because of non-local connections. This is akin to implicit wellbore constraints in conventional reservoir simulation and we have investigated several algorithms to improve solution times when many multiply defined nodes exist.

The add-mesh capability was developed because of the need to model reservoirs with highly deviated and even horizontal wellbores. The ability to create grids representing wells and tunnels allows accurate representation of gas and fluid flow in the vicinity of these structures. These wells can be created along an arbitrary path using hexahedral or NURB representations. By adding these well meshes to a background mesh, we have explored different structural representations and look for various grid effects or advantages to representing wells in this way. Adding, subtracting and melding are all operations that have been developed for further expansion of mesh creation. Wells can be added to a background mesh, subsets can be extracted, refined, then added back into the mesh. The work has produced a meshing code that is able to combine a grid that accurately reflects the tortuous path of a wellbore with a pre-existing reservoir model that may have many existing stratigraphic boundaries that must be maintained. The trick has been in regulating the amount of "excavated" grid when adding the wellbore mesh. This technology allows oil companies to evaluate the potential of long-reach horizontal wells for many applications where small surface facilities are demanded because of cost (off-shore) or environmental concerns (wildlife refuges).

The benchmarking of structured vs. unstructured grids has been carried out primarily by the University of Houston and Western Atlas Software. Here, the speed of structured grids (finite difference) is pitted against the ability of unstructured grids to represent the reservoir with more accuracy. The study used a commercial reservoir simulator retrofitted with an unstructured grid capability. In cases where there was a fault boundary, the unstructured mesh problem was very competitive with the standard finite-difference formulation.

The linear equation solver question is extremely important for unstructured grids. In order to take advantage of the solid modeling capability of unstructured grids, the coupled linear equations resulting from the material balance equations must be solved with an efficiency approaching that of structured grids. We have improved our unstructured linear equation solvers and have made them available for benchmarking to our university and industrial collaborators. We have also developed a massively parallel version of the equation solvers. This version of the equation solver uses an iterative technique to establish an incomplete LU decomposition for use as a preconditioner. The iterations typically number about twenty. Thus on a serial machine the solution takes twenty times longer. On a massively parallel machine the time is theoretically 20 times the CPU time for one node. For millions of nodes running on machines with thousands of processors, the payoff is obvious. The solver also uses a similar iterative technique to calculate forward elimination and back substitution on the preconditioned matrix. Coupled problems with two unknowns per node were considered and corresponding software developed. Simulation problems involving phase changes produce equation sets that are difficult to solve and require more preconditioner fill-in than the structure of the original matrix allows. These so-called higher-level, fill-in schemes have also been incorporated in our parallel work. One of the surprising outcomes of this work is that the higher-order, fill-in schemes only minimally affect the convergence rate of the iterative preconditioner.

The research started and completed in this project is continuing with support from the Advanced Computational Technology Initiative (ACTI) for domestic oil production. Major oil companies that have expressed interest include Shell, Amoco, ARCO, and Exxon. Major interested service companies include Western Atlas Software and Schlumberger. The major focus for the near -term will be on representing faults with offsets and developing linear equation solvers that are competitive with their finite-difference counterparts.